EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN-PH-EP-2015-035
19 February 2015

Precision measurement of the mass difference between light nuclei and anti-nuclei

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Abstract

The measurement of the mass differences for systems bound by the strong force has reached a very high precision with protons and anti-protons. The extension of such measurement from (anti-)baryons to (anti-)nuclei allows one to probe any difference in the interactions between nucleons and anti-nucleons encoded in the (anti-)nuclei masses. This force is a remnant of the underlying strong interaction among quarks and gluons and can be described by effective theories, but cannot yet be directly derived from quantum chromodynamics. Here we report a measurement of the difference between the ratios of the mass and charge of deuterons (d) and anti-deuterons ($\overline{\mathrm{d}}$), and ^{3}He and $^{3}\overline{\mathrm{He}}$ nuclei carried out with the ALICE (A Large Ion Collider Experiment) detector in Pb-Pb collisions at a centre-of-mass energy per nucleon pair of 2.76 TeV. Our direct measurement of the mass-over-charge differences confirm CPT invariance to an unprecedented precision in the sector of light nuclei. This fundamental symmetry of nature, which exchanges particles with anti-particles, implies that all physics laws are the same under the simultaneous reversal of charge(s) (charge conjugation C), reflection of spatial coordinates (parity transformation P) and time inversion (T).

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The measurement of the mass differences for systems bound by the strong force has reached a very high precision with protons and anti-protons[1, 2]. The extension of such measurement from (anti-)baryons to (anti-)nuclei allows one to probe any difference in the interactions between nucleons and anti-nucleons encoded in the (anti-)nuclei masses. This force is a remnant of the underlying strong interaction among quarks and gluons and can be described by effective theories[3], but cannot yet be directly derived from quantum chromodynamics. Here we report a measurement of the difference between the ratios of the mass and charge of deuterons (d) and anti-deuterons ($\bar{\mathrm{d}}$), and ^{3}He and $^{3}\overline{\mathrm{He}}$ nuclei carried out with the ALICE (A Large Ion Collider Experiment)[4] detector in Pb-Pb collisions at a centre-of-mass energy per nucleon pair of 2.76 TeV. Our direct measurement of the mass-over-charge differences confirm CPT invariance to an unprecedented precision in the sector of light nuclei[5, 6]. This fundamental symmetry of nature, which exchanges particles with anti-particles, implies that all physics laws are the same under the simultaneous reversal of charge(s) (charge conjugation C), reflection of spatial coordinates (parity transformation P) and time inversion (T). Heavy ions are collided at very high energies at the CERN Large Hadron Collider (LHC) to study matter at extremely high temperatures and densities. Under these conditions heavy-ion collisions are a copious source of matter and anti-matter particles and thus are suitable for an experimental investigation of their properties such as mass and electric charge. In relativistic heavy-ion collisions, nuclei and corresponding anti-nuclei are produced with nearly equal rates[7]. Their yields have been measured at the Relativistic Heavy Ion Collider (RHIC) by the STAR[8] and PHENIX[9] experiments and at the LHC by the ALICE[4] experiment. To date, the heaviest anti-nucleus which has been observed[7] is $^{4}\overline{\mathrm{He}}$ (anti-α); meanwhile, for lighter nuclei and anti-nuclei, which are more copiously produced, a detailed comparison of their properties is possible. This comparison represents an interesting test of CPT symmetry in an analogous way as done for elementary fermions[10, 11] and bosons[12], and for QED[13, 14] and QCD systems[1, 2, 15–17] (a particular example for the latter being the measurements carried out on neutral kaon decays[18]), with different levels of precision which span over several orders of magnitude. All these measurements can be used to constrain, for different interactions, the parameters of effective field theories that add explicit CPT violating terms to the Standard Model Lagrangian, such as the Standard Model Extension[19] (SME).

The measurements reported in this paper are based on the high-precision tracking and identification capabilities of the ALICE experiment[20]. The main detectors employed in this analysis are the ITS[21] (Inner Tracking System) for the determination of the interaction vertex, the TPC[22] (Time Projection Chamber) for tracking and specific energy loss ($\mathrm{d}E/\mathrm{d}x$) measurements, and the TOF[23] (Time Of Flight) detector to measure the time t_{TOF} needed by each track to traverse the detector. The combined ITS and TPC information is used to determine the track length (L) and the rigidity (p/z, where p is the momentum and z the electric charge in units of the elementary charge e) of the charged particles in the solenoidal 0.5 T magnetic field of the ALICE central barrel (pseudo-rapidity $|\eta| < 0.8$). Based on these measurements, we can extract the squared mass-over-charge ratio $\mu^2_{\mathrm{TOF}} \equiv (m/z)^2_{\mathrm{TOF}} = (p/z)^2\,[(t_{\mathrm{TOF}}/L)^2 - 1/c^2]$. The choice of this variable is motivated by the fact that μ^2 is directly proportional to the square of the time of flight, allowing to better preserve its Gaussian behaviour.

The high precision of the TOF detector, which determines the arrival time of the particle with a resolution of 80 ps[20], allows us to measure a clear signal for (anti-)protons, (anti-)deuterons and (anti-)^{3}He nuclei over a wide rigidity range ($1 < p/|z| < 4$ GeV/c). The main source of background, which is potentially of the same order of the signal, arises from tracks erroneously associated to a TOF hit. To reduce this contamination, a 2σ cut (where σ is the standard deviation) around the expected TPC $\mathrm{d}E/\mathrm{d}x$ signal is applied. Such a requirement strongly suppresses (to below 4%) this background for rigidities below $p/|z| < 2.0$ GeV/c for (anti-)deuterons and for all rigidities for (anti-)^{3}He (to below 1%). For each of the species under study, the mass is extracted by fitting the mass-squared distributions in narrow $p/|z|$ and η intervals, using a Gaussian with a small exponential tail that reflects the time signal distribution of the TOF detector. Examples of the mass-squared distributions for (anti-)deuterons and (anti-)^{3}He candidates are reported in Fig. 1 in selected rigidity intervals.

Using mass differences, rather than absolute masses, allows us to reduce the systematic uncertainties related to tracking, spatial alignment (affecting the measurement of the track momentum and length) and time calibration. Despite that, residual effects are still present, due to imperfections in the detector alignment and the description of the magnetic field, which can lead to position-dependent systematic uncertainties. In terms of relative uncertainties, the ones affecting the measurement of the momentum are the largest and independent of the mass, and are the same for all positive (negative) particles in a given momentum interval. It is therefore possible to correct the (anti-)deuteron and the (anti-)^{3}He masses by scaling them with the ratio between the (anti-)proton masses recommended by PDG[24] ($\mu^{\mathrm{PDG}}_{\mathrm{p}(\bar{\mathrm{p}})}$) and the ones measured in the analysis presented here ($\mu^{\mathrm{TOF}}_{\mathrm{p}(\bar{\mathrm{p}})}$), i.e. $\mu_{\mathrm{A}(\bar{\mathrm{A}})} = \mu^{\mathrm{TOF}}_{\mathrm{A}(\bar{\mathrm{A}})} \times (\mu^{\mathrm{PDG}}_{\mathrm{p}(\bar{\mathrm{p}})}/\mu^{\mathrm{TOF}}_{\mathrm{p}(\bar{\mathrm{p}})})$. These correction factors, which depend on the rigidity, deviate from unity by at most 1%. Conversely, systematic effects connected to the track-length measurement are mass dependent and cannot be completely accounted for using the above correction. However, they are expected to be symmetric for positive and negative particles when inverting the magnetic field. Any residual asymmetry is therefore indicative of remaining systematic uncertainties related to the detector conditions. In order to estimate them and keep these effects under control, both nuclei and anti-nuclei measurements are performed for two opposite magnetic field configurations and then averaged. Their half difference is taken as the estimate of this systematic uncertainty. Other sources of systematic uncertainties are evaluated by varying energy loss corrections applied to the reconstructed momentum, the range and the shape of the background function assumed in the fit of the mass-squared distributions and the track selection criteria. In particular, TPC $\mathrm{d}E/\mathrm{d}x$ cuts are varied between one and four standard deviations to probe the sensitivity of the fit results on the residual background, and a tracking quality cut on the distance of closest approach of the track to the vertex is varied to evaluate the influence of secondary particles on the measurement. The sources of systematic uncertainties are found to be fully correlated among all the rigidity intervals, except for those due to the fit procedure and the TPC selection criteria where the uncertainties are uncorrelated. For deuterons and anti-deuterons, the largest relative systematic uncertainties on $\Delta\mu/\mu$ come from the detector alignment ($\sim 0.7\times10^{-4}$), the TPC selection criteria ($\sim 0.7\times10^{-4}$) and the secondaries ($\sim 1.0\times10^{-4}$). For ^{3}He and $^3\overline{\mathrm{He}}$, they come from the energy loss corrections ($\sim 0.7\times10^{-3}$), the fit procedure ($\sim 0.5\times10^{-3}$) and the TPC selection criteria ($\sim 0.4\times10^{-3}$).

The (anti-)deuteron and (anti-)^{3}He masses are measured as the peak position of the fitting curves of the mass-squared distribution. The mass-over-charge ratio differences between the deuteron and ^{3}He and their respective anti-particle are then evaluated as a function of the rigidity of the track, as shown in Fig. 2. The measurements in the individual rigidity intervals are combined, taking into account statistical and systematic uncertainties (correlated and uncorrelated), and the final result is shown in the same figure with one and two standard deviation uncertainty bands. The measured mass-over-charge ratio differences are

$$\Delta\mu_{\mathrm{d}\bar{\mathrm{d}}} = [1.7 \pm 0.9(\mathrm{stat.}) \pm 2.6(\mathrm{syst.})] \times 10^{-4}\ \mathrm{GeV}/c^2\,, \tag{1}$$

$$\Delta\mu_{^3\mathrm{He}^3\overline{\mathrm{He}}} = [-1.7 \pm 1.2(\mathrm{stat.}) \pm 1.4(\mathrm{syst.})] \times 10^{-3}\ \mathrm{GeV}/c^2\,, \tag{2}$$

corresponding to

$$\frac{\Delta\mu_{\mathrm{d}\bar{\mathrm{d}}}}{\mu_{\mathrm{d}}} = [0.9 \pm 0.5(\mathrm{stat.}) \pm 1.4(\mathrm{syst.})] \times 10^{-4}\,, \tag{3}$$

$$\frac{\Delta\mu_{^3\mathrm{He}^3\overline{\mathrm{He}}}}{\mu_{^3\mathrm{He}}} = [-1.2 \pm 0.9(\mathrm{stat.}) \pm 1.0(\mathrm{syst.})] \times 10^{-3}\,, \tag{4}$$

where μ_{d} and $\mu_{^3\mathrm{He}}$ are the values recommended by CODATA[25]. The mass-over-charge differences are compatible with zero within the estimated uncertainties, in agreement with CPT invariance expectations.

Given that$z_{\bar{\mathrm{d}}} = -z_{\mathrm{d}}$ and $z_{^3\overline{\mathrm{He}}} = -z_{^3\mathrm{He}}$ as for the proton and anti-proton[1, 2], the mass-over-charge differences in Eq. 1 and Eq. 2 and the measurement of the mass differences between proton and anti-proton[1, 2] and between neutron and anti-neutron[15, 16] can be used to derive the relative binding energy differences between the two studied particle species. We obtain

$$\frac{\Delta\varepsilon_{\mathrm{d}\bar{\mathrm{d}}}}{\varepsilon_{\mathrm{d}}} = -0.04 \pm 0.05\ (\mathrm{stat.}) \pm 0.12\ (\mathrm{syst.})\,, \tag{5}$$

$$\frac{\Delta\varepsilon_{^3\mathrm{He}^3\overline{\mathrm{He}}}}{\varepsilon_{^3\mathrm{He}}} = 0.24 \pm 0.16\ (\mathrm{stat.}) \pm 0.18\ (\mathrm{syst.})\,, \tag{6}$$

where $\varepsilon_A = Zm_{\mathrm{p}} + (A-Z)m_{\mathrm{n}} - m_A$, being m_{p} and m_{n} the proton and the neutron mass values recommended by PDG[24] and m_A the mass value of the nucleus with atomic number Z and mass number A, recommended by CODATA[25]. This quantity allows one to explicitly isolate possible violations of the CPT symmetry in the (anti-)nucleon interaction from the one connected to the (anti-)nucleon masses, the latter being constrained with a precision of 7×10^{-10} for the proton/anti-proton system[1, 2]. Our results and the comparisons with previous mass difference measurements for (d-$\overline{\mathrm{d}}$)[26, 27] and (^{3}He-$^3\overline{\mathrm{He}}$)[28], as well as binding energy measurements for (d-$\overline{\mathrm{d}}$)[29, 30] are reported in Fig. 3.

We have shown that the copious production of (anti-)nuclei in relativistic heavy-ion collisions at the LHC represents a unique opportunity to test the CPT invariance of nucleon-nucleon interaction using light nuclei. In particular, we have measured the mass-over-charge ratio differences for deuteron and ^{3}He. The values are compatible, within uncertainties, with zero and represent a CPT invariance test in systems bound by nuclear forces. The results reported here (Fig. 3, left) represent the highest precision direct measurements of mass differences in the sector of nuclei and they improve by one to two orders of magnitude analogous results originally obtained more than 40 years ago[26–28], and precisely 50 years ago for the anti-deuteron[26, 27]. Remarkably such an improvement is reached in an experiment which is not specifically dedicated to test the CPT invariance in nuclear systems. In the forthcoming years the increase in luminosity and center-of-mass energy at the LHC will allow to push forward the sensitivity of these measurements, and possibly to extend the study to (anti-)^{4}He. Given the equivalence between mass and binding energy differences, our results also improve (Fig. 3, right) by a factor two the constraints on CPT invariance inferred by existing measurements[29, 30] in the (anti-)deuteron system. The binding energy difference has been determined for the first time in the case of (anti-)^{3}He, with a relative precision comparable to the one obtained in the (anti-)deuteron system.

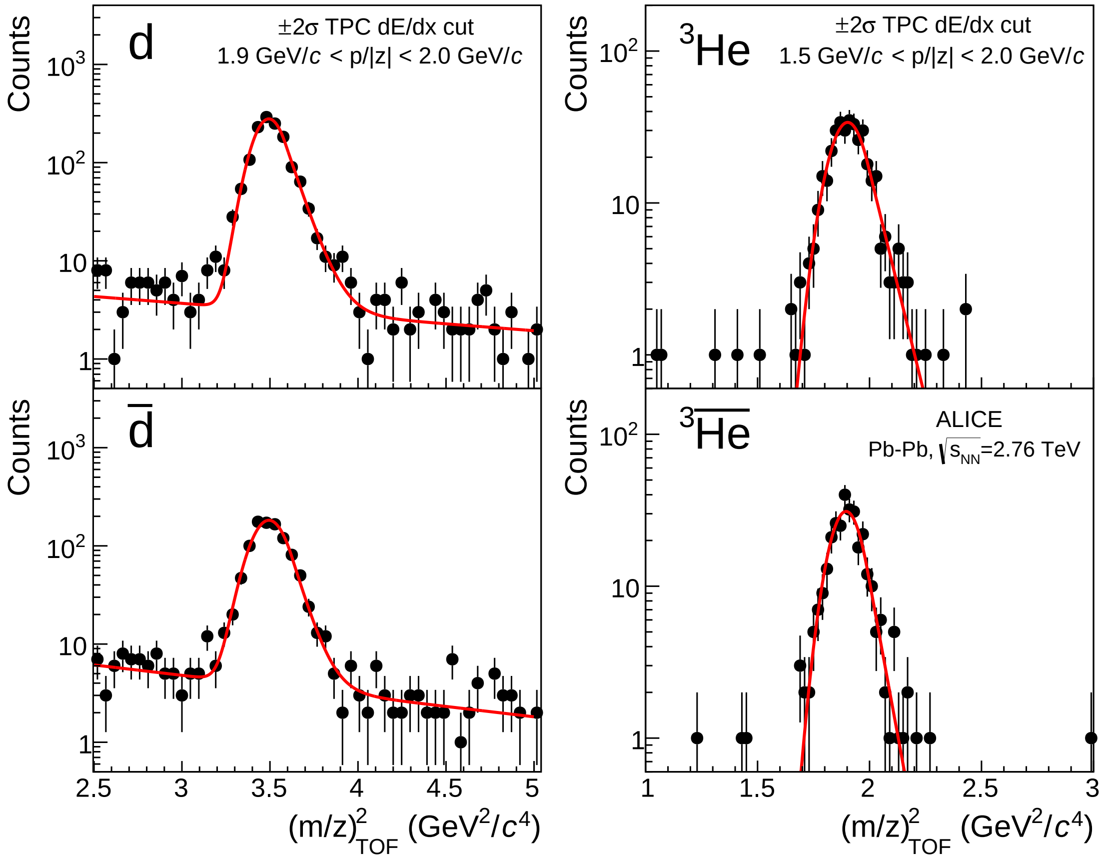

Fig. 1: Examples of squared mass-over-charge ratio distributions for deuterons (left) and ^{3}He (right) in selected rigidity intervals. Particle and anti-particle spectra are in the top and bottom plots, respectively. The fit function (red curve) also includes, for the (anti-)deuteron case, an exponential term to describe the background. In the rigidity intervals shown here the background is about 4% for (anti-)deuterons, while it is 0.7% for ^{3}He and $^3\overline{\text{He}}$.

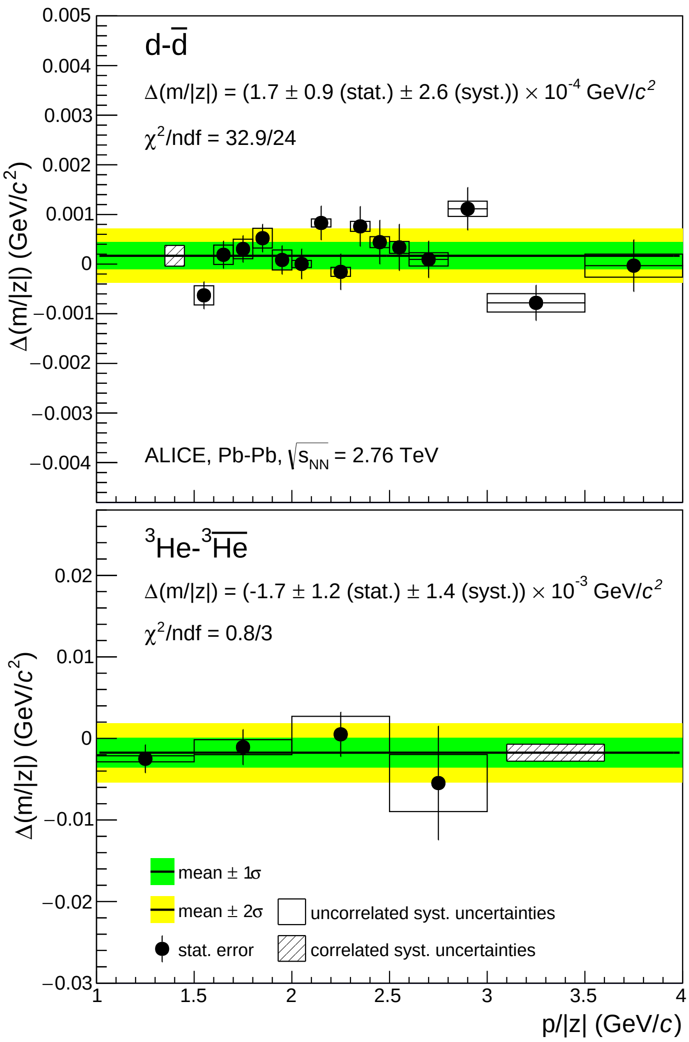

Fig. 2: The d-$\overline{\rm d}$ (top) and ^{3}He-$^3\overline{\rm He}$ (bottom) mass-over-charge ratio difference measurements as a function of the particle rigidity. Vertical bars and open boxes show the statistical and the uncorrelated systematic uncertainties (standard deviations), respectively. Both are taken into account to extract the combined result in the full rigidity range, together with the correlated systematic uncertainty, which is shown as a box with tilted lines. Also shown are the 1σ and 2σ bands around the central value, where σ is the sum in quadrature of the statistical and systematic uncertainties.

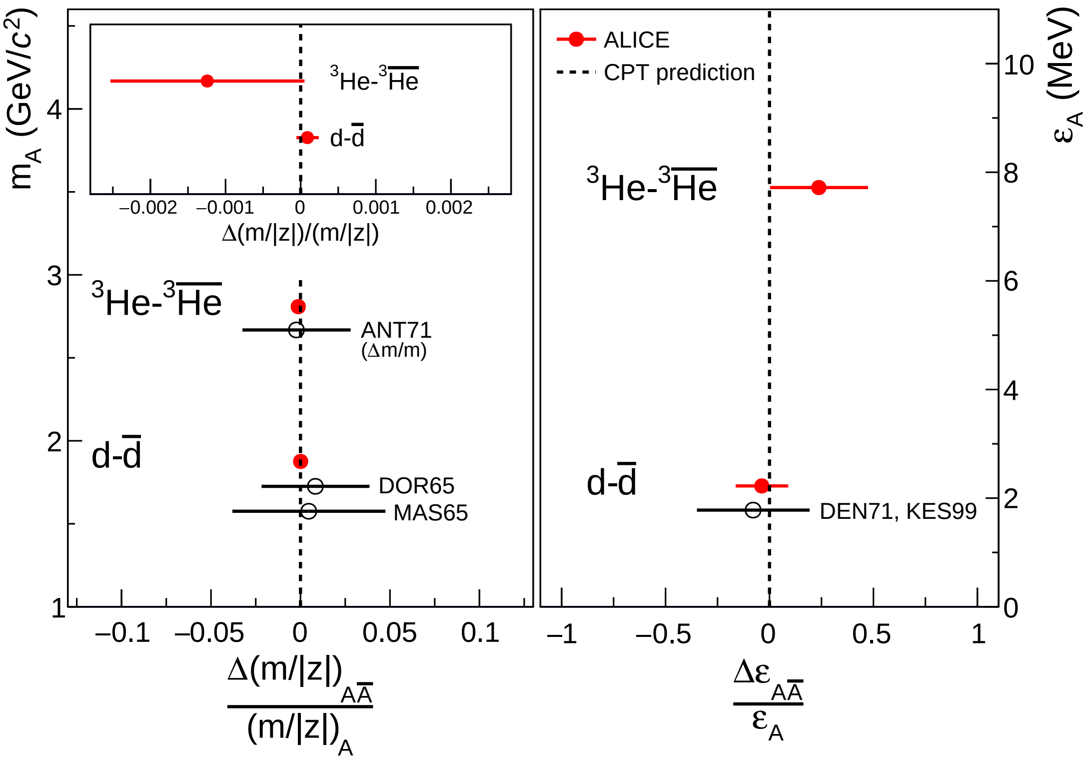

Fig. 3: The ALICE measurements for d-$\bar{\text{d}}$ and ^{3}He-$^3\overline{\text{He}}$ mass-over-charge ratio differences compared with CPT invariance expectation (dotted lines) and existing mass measurements MAS65[26], DOR65[27] and ANT71[28] (left panel). The inset shows the ALICE results on a finer $\Delta(m/z)/(m/z)$ scale. The right panel shows our determination of the binding energy differences compared with direct measurements from DEN71[29] and KES99[30]. Error bars represent the sum in quadrature of the statistical and systematic uncertainties (standard deviations).

Acknowledgements

The ALICE Collaboration would like to thank all its engineers and technicians for their invaluable contributions to the construction of the experiment and the CERN accelerator teams for the outstanding performance of the LHC complex. The ALICE Collaboration gratefully acknowledges the resources and support provided by all Grid centres and the Worldwide LHC Computing Grid (WLCG) collaboration. The ALICE Collaboration acknowledges the following funding agencies for their support in building and running the ALICE detector: State Committee of Science, World Federation of Scientists (WFS) and Swiss Fonds Kidagan, Armenia, Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq), Financiadora de Estudos e Projetos (FINEP), Fundação de Amparo à Pesquisa do Estado de São Paulo (FAPESP); National Natural Science Foundation of China (NSFC), the Chinese Ministry of Education (CMOE) and the Ministry of Science and Technology of China (MSTC); Ministry of Education and Youth of the Czech Republic; Danish Natural Science Research Council, the Carlsberg Foundation and the Danish National Research Foundation; The European Research Council under the European Community's Seventh Framework Programme; Helsinki Institute of Physics and the Academy of Finland; French CNRS-IN2P3, the 'Region Pays de Loire', 'Region Alsace', 'Region Auvergne' and CEA, France; German Bundesministerium fur Bildung, Wissenschaft, Forschung und Technologie (BMBF) and the Helmholtz Association; General Secretariat for Research and Technology, Ministry of Development, Greece; Hungarian Orszagos Tudomanyos Kutatasi Alappgrammok (OTKA) and National Office for Research and Technology (NKTH); Department of Atomic Energy and Department of Science and Technology of the Government of India; Istituto Nazionale di Fisica Nucleare (INFN) and Centro Fermi - Museo Storico della Fisica e Centro Studi e Ricerche "Enrico Fermi", Italy; MEXT Grant-in-Aid for Specially Promoted Research, Japan; Joint Institute for Nuclear Research, Dubna; National Research Foundation of Korea (NRF); Consejo Nacional de Cienca y Tecnologia (CONACYT), Direccion General de Asuntos del Personal Academico(DGAPA), México, :Amerique Latine Formation academique European Commission(ALFA-EC) and the EPLANET Program (European Particle Physics Latin American Network) Stichting voor Fundamenteel Onderzoek der Materie (FOM) and the Nederlandse Organisatie voor Wetenschappelijk Onderzoek (NWO), Netherlands; Research Council of Norway (NFR); National Science Centre, Poland; Ministry of National Education/Institute for Atomic Physics and Consiliul Naional al Cercetrii tiinifice - Executive Agency for Higher Education Research Development and Innovation Funding (CNCS-UEFISCDI) - Romania; Ministry of Education and Science of Russian Federation, Russian Academy of Sciences, Russian Federal Agency of Atomic Energy, Russian Federal Agency for Science and Innovations and The Russian Foundation for Basic Research; Ministry of Education of Slovakia; Department of Science and Technology, South Africa; Centro de Investigaciones Energeticas, Medioambientales y Tecnologicas (CIEMAT), E-Infrastructure shared between Europe and Latin America (EELA), Ministerio de Economía y Competitividad (MINECO) of Spain, Xunta de Galicia (Consellería de Educación), Centro de Aplicaciones Tecnolgicas y Desarrollo Nuclear (CEADEN), Cubaenergía, Cuba, and IAEA (International Atomic Energy Agency); Swedish Research Council (VR) and Knut & Alice Wallenberg Foundation (KAW); Ukraine Ministry of Education and Science; United Kingdom Science and Technology Facilities Council (STFC); The United States Department of Energy, the United States National Science Foundation, the State of Texas, and the State of Ohio; Ministry of Science, Education and Sports of Croatia and Unity through Knowledge Fund, Croatia. Council of Scientific and Industrial Research (CSIR), New Delhi, India

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